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ELASTRONICS LABORATORIES

QUANTOMICS, INC.

GASEOUS FLOW CALIBRATION SYSTEM BASED ON MULTI-RANGE ADJUSTABLE-MANIFOLD FLOWMETER CONCEPT

I. GENERAL

The QL Adjustable-Manifold Multi-range Gaseous Flowmeter Calibration System is designed to fill a need for highly precise and unusually wide range flow measurement, calibration, control, and automatic fluid transfer in aerospace applications. This system can be used with gaseous, cryogenic and liquid effluents. it provides very high resolution and accurate measurement at high flowrates by summing the multi-channel frequency outputs; yet the same system also enables the metering of low flowrates with each individual flowmeter. In this system, a rigorously computed smooth-transition manifold design is used, which in conjunction with the adjustable Foettinger-Frey vanes, enable the manifold flowmeter system to achieve the following performance features:

a) Insures proper distribution of the fluid flow between the individual flow channels under various pressure-head, flowrate, and fluid characteristics.

b) Provides means for the precise adjustment of flow distribution with a minimum of detrimental fluid-dynamic phenomena, such as serious cavitation, cross-over transient, vortex, swirling, and other undesirable hydrodynamic and acoustic phenomena.

c) Facilitates the use of a number of high-resolution, smaller-sized flowmeters for the precise measurement of large amounts of flow, while at the same time insures that the properties of the effluent (e.g., density) are maintained essentially the same in all flow channels. This can only be done if the distribution of the flow can be adjusted and divided smoothly and evenly.

d) Drastically reduces the pressure drop and flow impedance at high flow rates.

With a passive type of manifold, it would be virtually impossible to satisfy the above features while achieving the proper distribution of flow among a multiplicity of channels; as such, the passive manifold is incapable of highly accurate measurement, calibration, and control functions of many channels. Such disadvantages are eliminated in the present adjustable-manifold flowmeter.

II. DESIGN OBJECTIVES

1. The Manifold Flowmeter System is mainly intended for gaseous flow calibration, although in the design process one of the purposes is to render the same system equally effective for the calibration and measurement of cryogenic fluids and liquids with or without the simplest adaptation or minimum modification. By achieving such goals, the present system can be used as a high accuracy gaseous-liquid-cryogenic transfer standard which would be invaluable to the efficient and economical performance of many difficult measurement and calibration tasks in aerospace programs.

2. A second design goal is to render the system sufficiently portable and compact while, at the same time, can adequately withstand higher operating pressure; the choice of the materials and components is based on the considerations of strength, non-corrosiveness, system rigidity and ruggedness, and compatibility with cryogenic operations. Vacuum jacketing and insulation can be

easily added to the present system for cryogenic operations.

3. Operating Pressure - The system is designed for safe and reliable operation at operating pressure of 3500 psia; the proof pressure is 8700 psia.

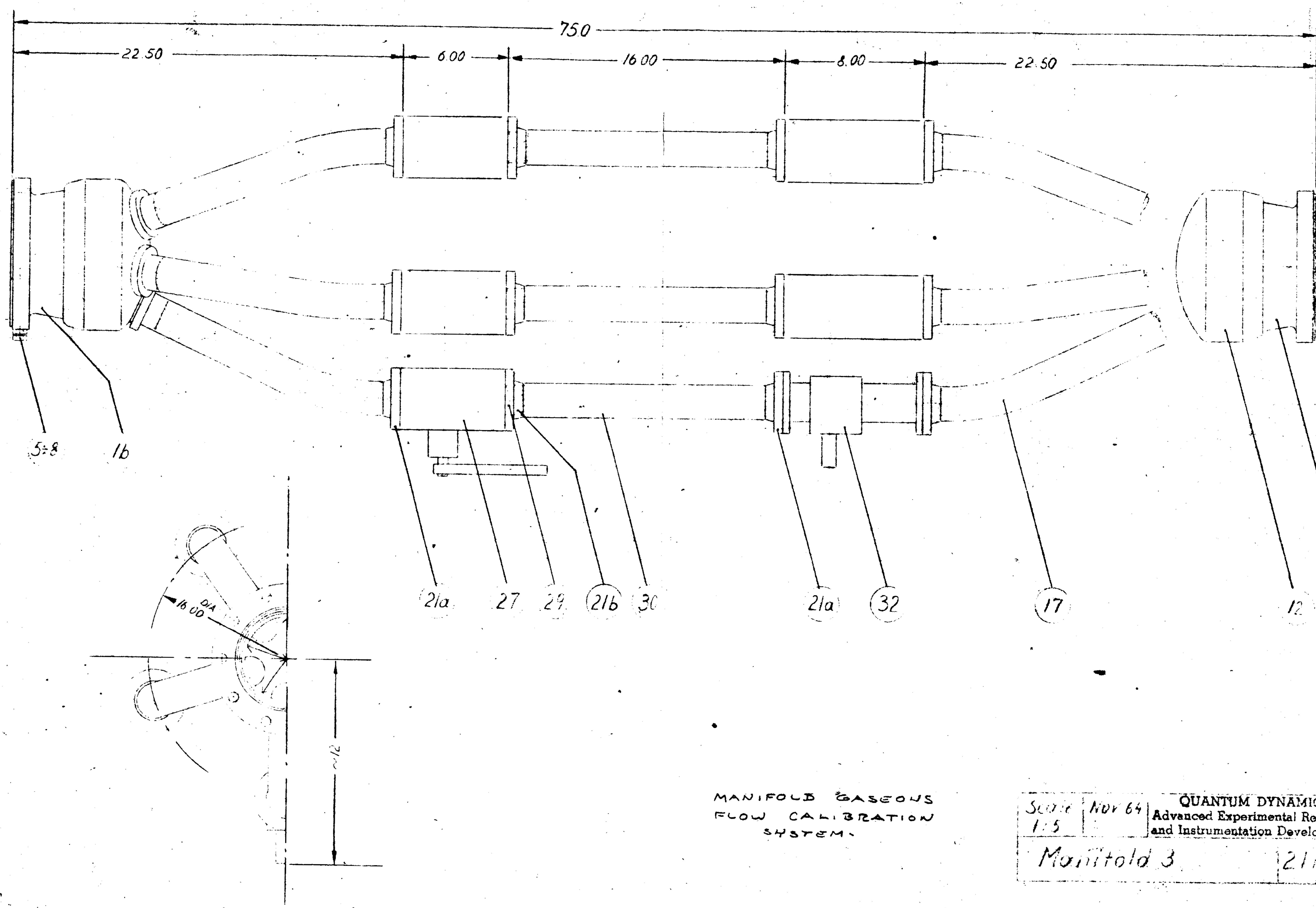
4. Flow Range - For gaseous flow calibration, each individual 2-inch flowmeter has a flow range of from 2 to 1,000 CFM, although it is recommended that it be used within the range of 2 to 750 CFM. Thus, the entire system, consisting of five (5) flowmeter channels has a flow range of from 2 to 5000 CFM, although it is recommended that for routine calibrations, this be limited to 2 to 3750 CFM. While calibration above this range is possible, its period should be kept appropriately short. The flowmeters are designed for reliable operation at very high frequency output and flowrates. They have exceptionally long bearing life and ruggedness as compared to ordinary flowmeters.

5. Degree of Flow Equalization Between Flow Channels - Through correct adjustment of the valves, and trimming the Foettinger-Frey vanes, the distribution of flow between channels can be adjusted so that the flowrates in the individual channels are within 2 per cent from each other. Nevertheless, it must be pointed out that such high degree of equalization is not strictly necessary for accurate calibration: as long as the flow distribution is kept within 10% from each other, the system will perform satisfactorily for ordinary flow calibration purposes.

6. Although the main purpose of the present system, using QL turbine flowmeters, is designed to provide volumetric flowrate calibration; it is designed with the view that, with its built-in pressure and temperature taps, suitable measurement and electronic computing devices (see sections on Mass Flow Calibration), the same system can provide highly accurate mass flow calibration for gases.

MANIFOLD GASEOUS
FLOW CALIBRATION
SYSTEM -

Part No.	Title, Specification	Material	Required
1a	Housing	St.St.	1
1b	Housing	St.St.	1
2	O-Ring, Parker 2-166	N 105-6	4
3	O-Ring, Parker 2-161	N 105-6	2
4	O-Ring, Parker 2-159	N 105-6	2
5	Vane Shaft	St.St.	5
6	O-Ring, Parker 2-10	N 105-6	10
7	Screw Bushing	St.St.	5
8	Nut	St.St.	5
9			
10	Insert	Al-Alloy	2
11	Pin .104 x .70	St.St.	4
12	Cap	St.St.	2
13	Location Screw	St.St.	4
14	Screw Bushing	St.St.	10
15	Set Screw No.5-44	St.St.	10
16			
17	Elbow	St.St.	10
18	Neck	St.St.	10
19	O-Ring, Parker 2-34	N 105-6	10
20	O-Ring, Parker 2-32	N 105-6	30
21a	Flange	St.St.	15
21b	Flange	St.St.	5
23	Machine Bolt 5/16-24	St.St.	160
24	Nut 5/16-24	St.St.	
25	Locking Washer	St.St.	
26	O-Ring, Parker 2-35	N 105-6	20
27	Ball Valve	St.St.	5
28			
29	Flow Straightener	St.St.	5
30	Tube	St.St.	5
31			
32	Flowmeter	St.St.	5



MANIFOLD GASEONS
FLOW CALIBRATION
SYSTEM.

Scale 1:5	Nov 64	QUANTUM DYNAMICS Advanced Experimental Research and Instrumentation Development
Manifold 3		2111

Fig. 1.

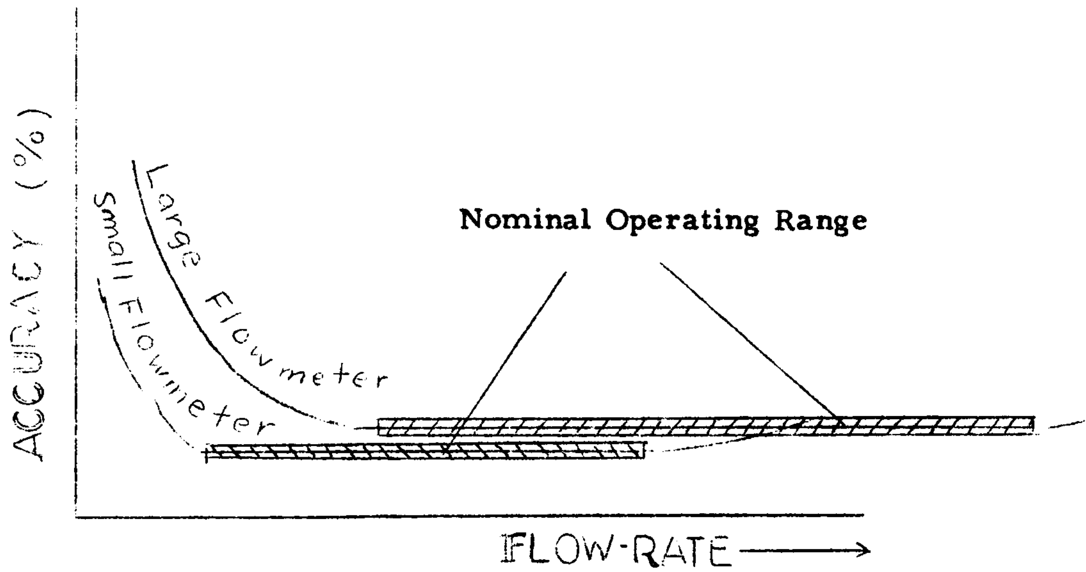
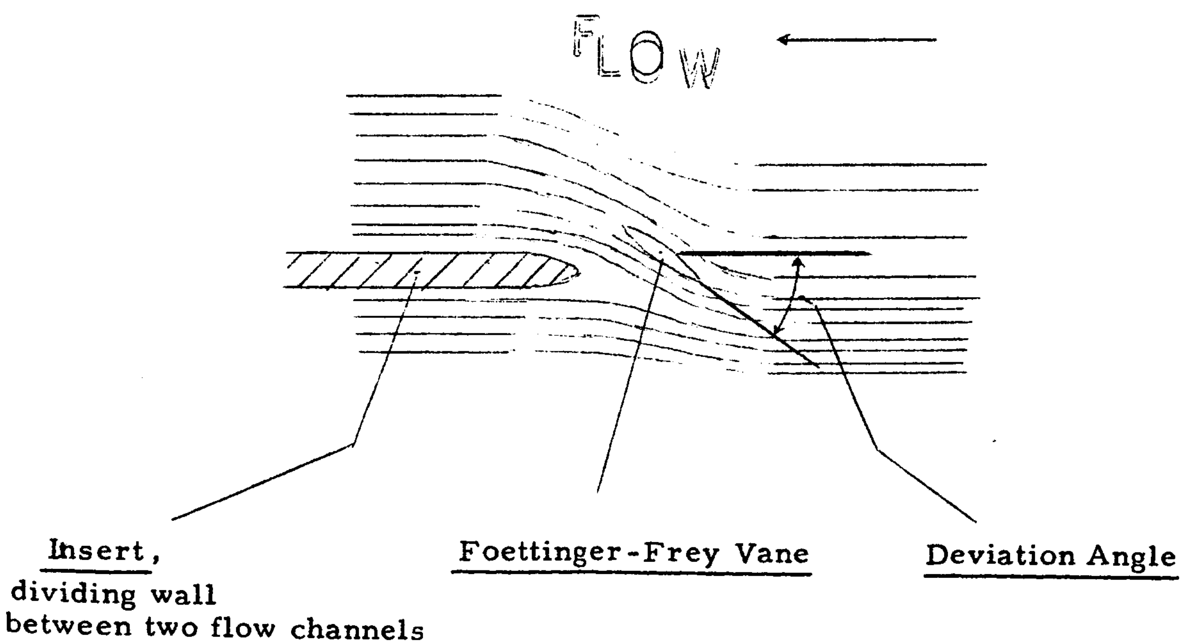

ACCURACY (%)
Large Flowmeter
Small Flowmeter
Nominal Operating Range
FLOW-RATE

Fig. 2.


FLOW
Insert,
dividing wall
between two flow channels
Foettinger-Frey Vane
Deviation Angle

The commercial ball valves should be selected for the working pressure of 3500 PSI and the proof pressure of 5250 PSI. However, "working" may not necessarily be defined as "capable of being turned on or off under pressure". The operation of those valves can take place without pressure in the manifold; a main valve within the supply line should be closed first.

Gaseous Flowmeters

The present manifold system accommodates five (5) 2-inch size Quantomics-Liu Gaseous/Cryogenic Flowmeters, Model QL-WRG-NA2SS, manufactured by Quantum Dynamics, Tarzana, California. These flowmeters are designed for operating pressure of 3500 psia and helium leak test at 6000 psia. This type of flowmeter is designed for gaseous, cryogenic fluids and liquid flow measurement, and can serve as an inter-correlating transfer-standard for such fluids.

The through-flow I.D. of the 2-inch QL flowmeters is 1.781". However, these units can be supplied with standard low-flowrate flowmeter inserts which are easily adapted to the same flowmeter housing, thereby extending the low flow calibration capability of the present system by a considerable margin. For instance, flowmeter insert with turbine assembly of 3/4-inch size, I.D. 0.656-inches has a flow range of from 0.3 to 12 CFM at high count-rate; 1/2-inch flowmeter insert can meter down to 0.05 CFM (up to 5 CFM) at high resolution.

For some technical description of QL flowmeters and its cryotronic pickup see Quantum Dynamics' Bulletins 5.1 and 5.2.

IV.

Design Philosophy of the Manifold Flowmeter System

Any turbine flowmeter performs at its best accuracy only over a certain range of flowrates. In general, the limiting Reynolds numbers establish the operational capacity for each particular design, and for each nominal size of a flowmeter (see Fig. 1). Since one flowmeter cannot measure "all flowrates"; a single -flowmeter calibration installation has to be a compromise between accuracy and range. But "compromise" contradicts "calibration accuracy", which is one of the main objectives of any calibration facility.

The principle of "manifolding", which means dividing and re-uniting a fluid flow under restriction of pressure losses, provides a solution to the problem by combining the performance requirements of wide range with highest accuracy.

As Fig. 1 shows: a turbine flowmeter's accuracy rapidly deteriorates when the flowrate is below or above certain values. Such deterioration of accuracy is, in general, slower when the flowrate is beyond the higher limit than when it is below the lower limit of the nominal flowrates. Small meter performs at its best in the low flow range, while a larger meter provides the desirable extension of range without sacrificing accuracy: the combination of such two flowmeters within one facility would then provide the wide-range superiority of a "two-meter" assembly over the "one (large) meter" assembly. Although it would appear that pure mathematical considerations favor the building block concept of arranging the calibration facilities according to decimal units of flow range, for example, "one", "two", "five", "ten", etc.) this method would require the assembly of different diameters of tubing, valves, meters, unions, etc., which, from the standpoint of practical engineering, would be less preferable than employing only one size diameter for all components within the combination. Even this "one-size" approach departs from the optimal concept of decimal arrangement; the loss in accuracy would be kept to a minimum, since statistical investigations have shown that there are some averaging effects when several flowmeters are operated in parallel.

The present calibration facility utilizes a manifolding design of 5 individual flow branches, or flow channels, having the same nominal tube diameter of 2 inches. The supply line is of 5-inch nominal pipe size schedule 80. During the flow-through process, the main fluid experiences some acceleration during the transition from the 5" pipe over the manifold to the sum of five 2" tubes. This slight acceleration is considered fluid-dynamically preferable to any deceleration, for theoretically perfect mathematical match of the flow cross-section is not considered economically justifiable in view of the availability of standard stock of tubes and pipes. Due to these over-all considerations, an accelerating flow is preferred in the present design, for in this case there is less vorticity which is detrimental to the flowmeter accuracy. Although there is decelerating flow in the downstream end, namely, in the recombinating manifold and which would result in some energy loss: this is of no concern to the flowmeter function, since the flow has already been measured at a previous station.

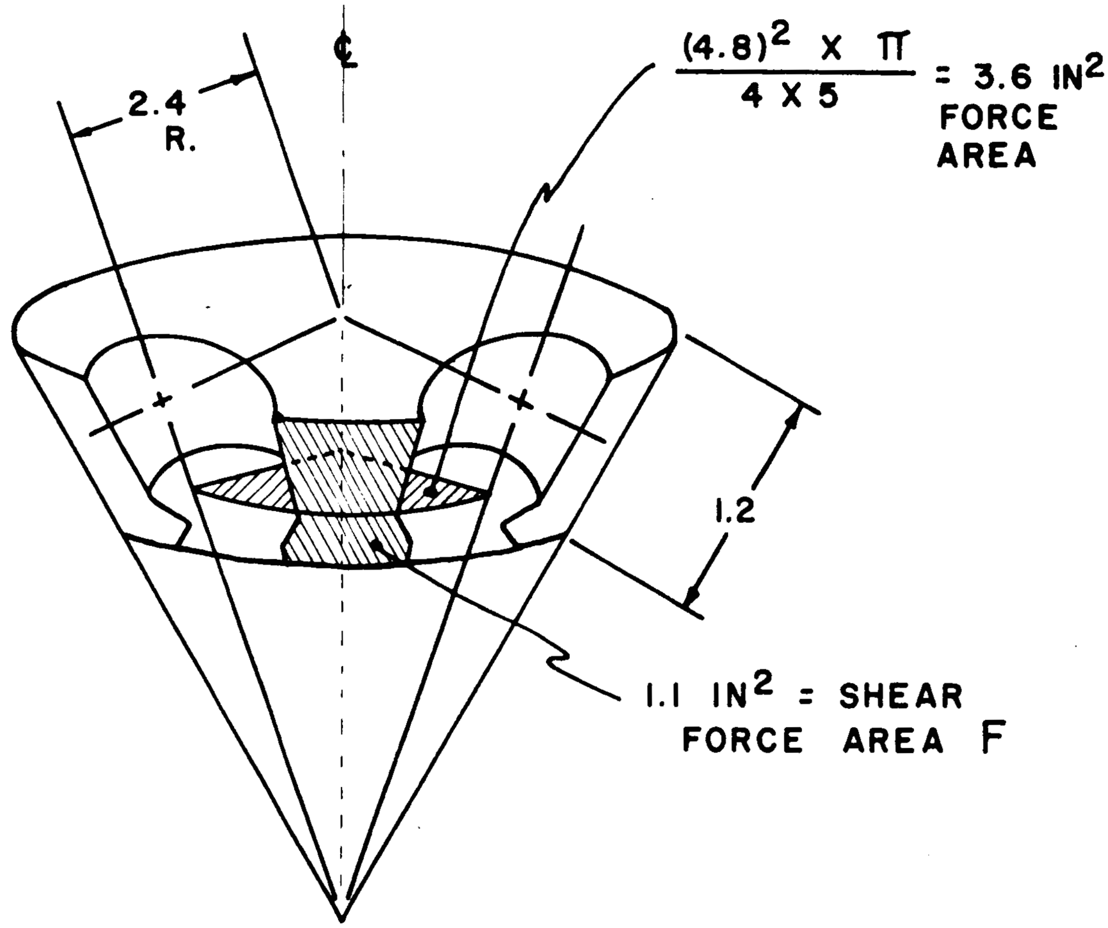
During a calibration procedure over a wide flowrate range, the individual flow branches are to be switched on, and added to each other, in a "register" fashion. The manifold principle thus provides a higher degree of versatility as compared to a single flowmeter facility. Flowmeters can be shut off or removed while the operation is continued with fewer or even only one meter in service.

The switching is accomplished by operation of ball valves. Only this kind of valve delivers full flow without disturbance. The whole manifold system is designed with emphasis on the smallest possible energy loss in every element along the flow path. A specially developed flow divider insert is contained within the manifold housing. It converts the arriving circular flow cross-section into 5 pie-shaped parts while effecting a gradual transition from the pie shaped section to a circular shaped flow of smaller cross-section area at the exit end of the inlet-manifold housing-cap. This circular cross-section is congruent with the connecting manifold tubes. Each of the 5 tubes experiences only a small radial bend before they enter the ball valve housings. The main flow straightener for each channel is located inside the flanged connection between the valve and its adjacent tubing. Thus, the flow straightening process is completed within the following straight tubing section before the fluid's arrival at the flowmeters. By this time, only a minimum of residual, but evenly distributed, micro-vorticity is permitted to enter the flowmeter housing which itself provides a final flow straightening process of its own.

If for certain special calibration or comparison tasks it should be required (for a certain flowrate range) to equalize several flow channels with the same (partial) flowrates, then a coarse rate adjustment can be made by operating the ball valves. The fine flow equalization is to be accomplished by adjusting the deviation angle of the vanes (Fig. 2) which are located within the flange of the inlet manifold housing. The Foettinger-Frey effect of those vanes induces a vernier flow deviation without any traceable pressure drop or discontinuities in the control program.

V.

SOME SAMPLE STRENGTH CALCULATIONS FOR CRITICAL ELEMENTS OF THE SYSTEM

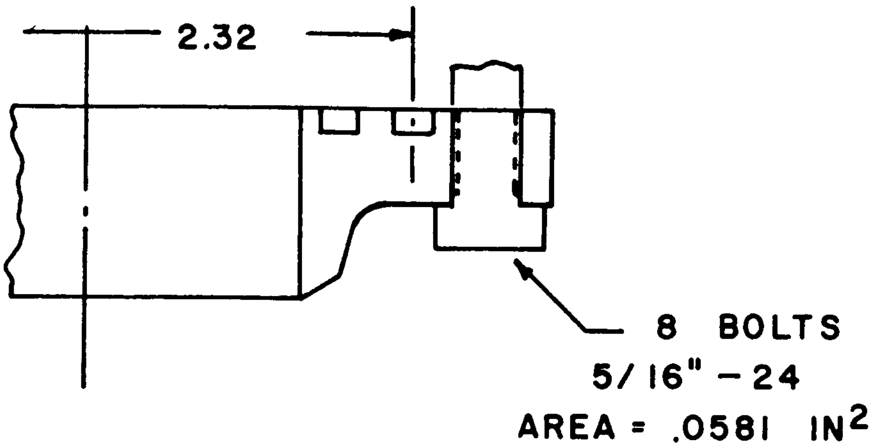


CAP — 12

$P_{WORK} = 3500$ PSI ; $P_{TEST} = 5250$ PSI

DOME WALL SHEAR — STRESS IN PLANE F :

$$\sigma_{SH} = \frac{5250 \times 3.6}{1.1} = \underline{\underline{20{,}000 \text{ PSI}}}$$



MACHINE BOLT — 23

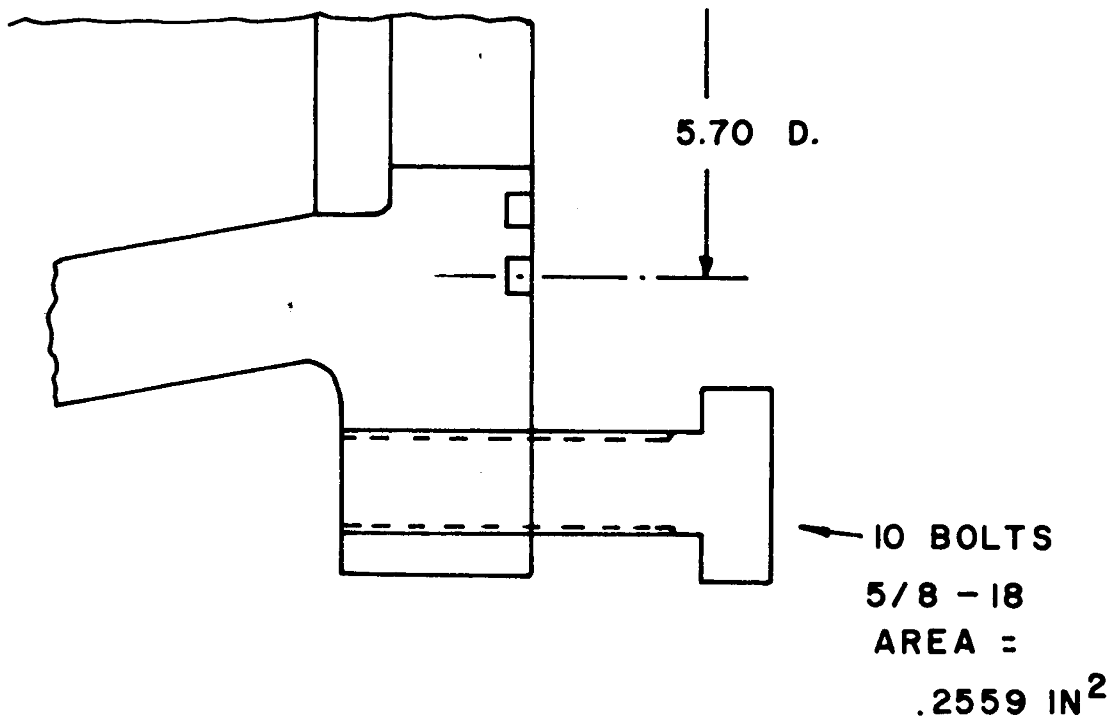
$P_{WORK} = 3500$ PSI ; $P_{TEST} = 5250$ PSI

AXIAL FORCE :

$$P = \frac{(2.32)^2 \times \pi \times 5250}{4} = \underline{22,200 \text{ Pd}}$$

$$P_{BOLT} = \frac{22,200}{8} = \underline{\underline{2,780 \text{ Pd}}}$$

$$\sigma = \frac{2,780}{.0581} = \underline{\underline{47,800 \text{ PSI}}}$$



MACHINE BOLT AT
HOUSING – 1 FLANGE

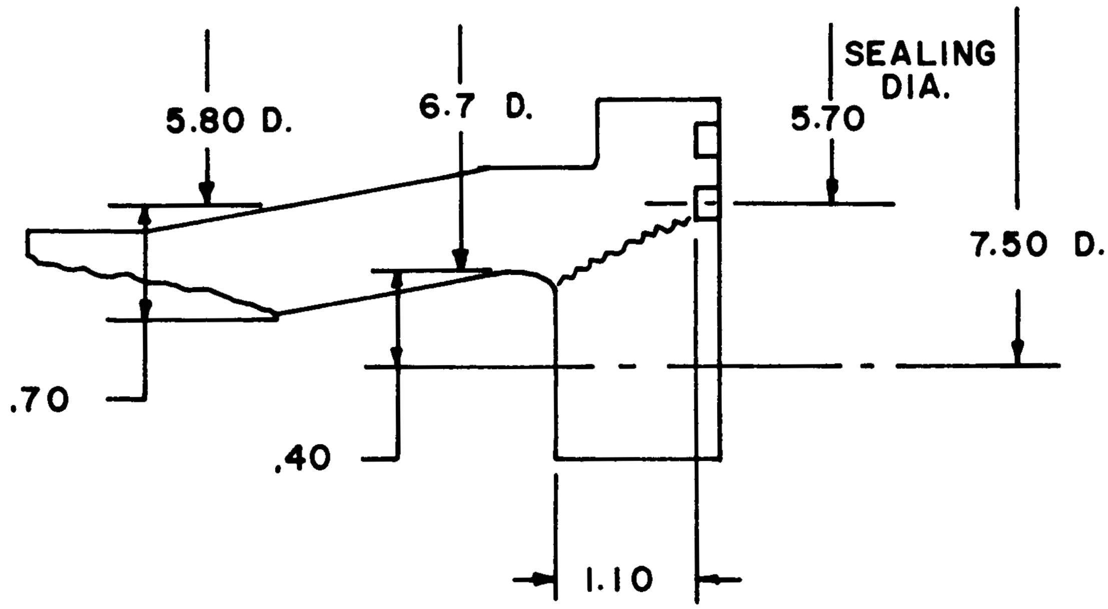
$P_{WORK} = 3500$ PSI $\qquad P_{TEST} = 5250$ PSI

AXIAL FORCE :

$$P = \frac{(5.70) \times \pi \times 5250}{4} = \underline{135{,}000 \text{ Pd}}$$

$$P_{BOLT} = \frac{135{,}000}{10} = \underline{13{,}500 \text{ Pd}}$$

$$\sigma = \frac{13{,}500}{.2559} = \underline{\underline{52{,}800 \text{ PSI}}}$$



HOUSING — I

P_{WORK} = 3500 PSI ; P_{TEST} = 5250 PSI

A) WALL STRESS :

$$\sigma = \frac{5.8 \times 5250}{2 \times .70} = \underline{\underline{21,800 \text{ PSI}}}$$

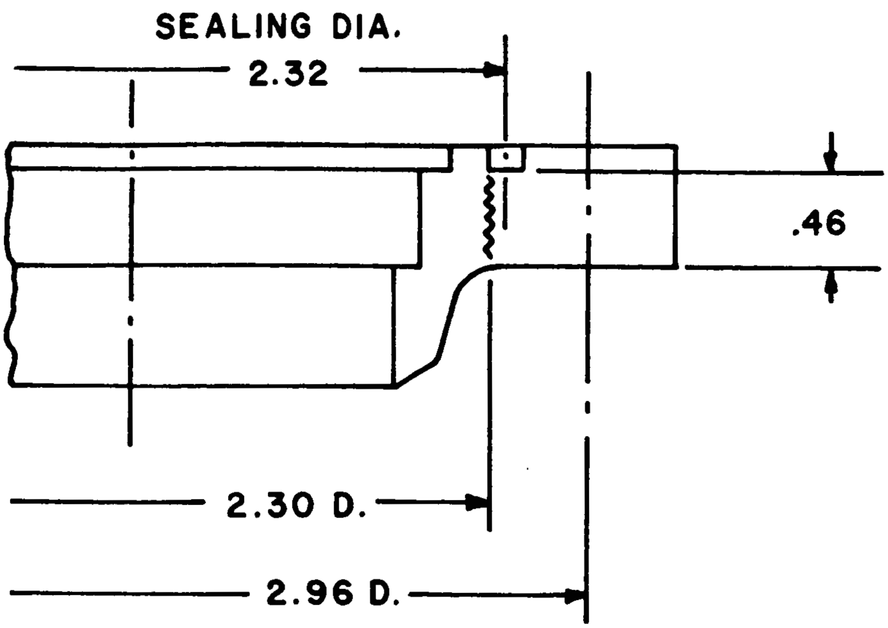
B) AXIAL FORCE :

$$P = \frac{(5.70)^2 \times \pi \times 5250}{4} = \underline{\underline{135,000 \text{ Pd}}}$$

C) <u>FLANGE BENDING STRESS :</u>

$$\sigma = \frac{135,000 \times .40 \times 6}{6.70 \times \pi \times (1.10)^2} = \underline{\underline{12,800 \text{ PSI}}}$$

(SAME ADDITION IN STRESS DUE TO SHEAR FORCE, NOTCH EFFECT AND BOLT HOLES IS ESTIMATED TO BE LESS THAN 30 %)



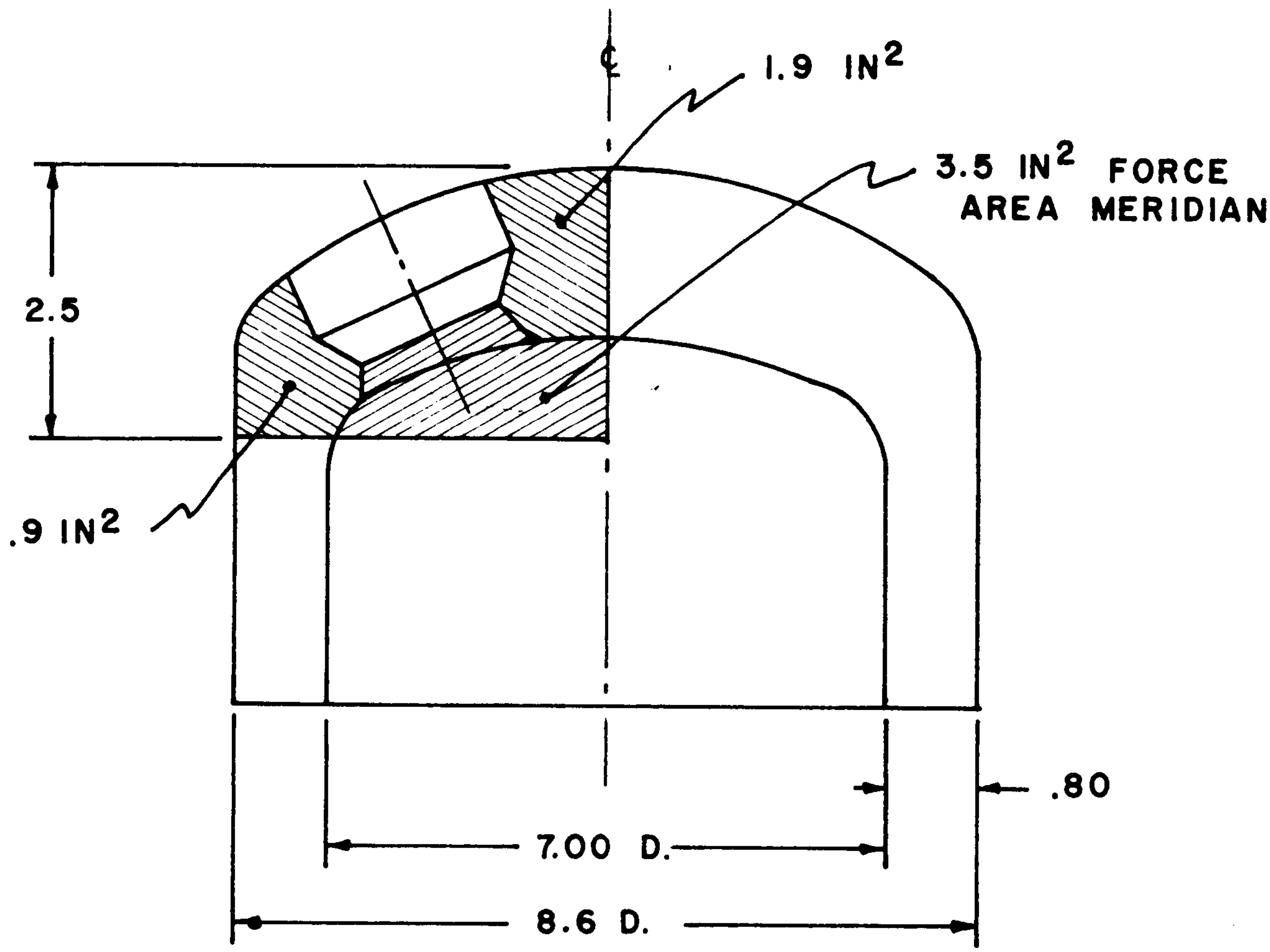
FLANGE — 21 b

P_{WORK} = 3500 PSI ; P_{TEST} = 5250 PSI

$$\text{AXIAL FORCE } P = \frac{(2.32)^2 \times \pi \times 5250}{4} = \underline{22{,}200 \text{ Pd}}$$

<u>FLANGE</u> <u>BENDING</u> <u>STRESS</u> :

$$\sigma = \frac{22{,}200 \times .33 \times 6}{2.3 \times \pi \times (.46)^2} = \underline{\underline{28{,}800 \text{ PSI}}}$$



CAP — 12

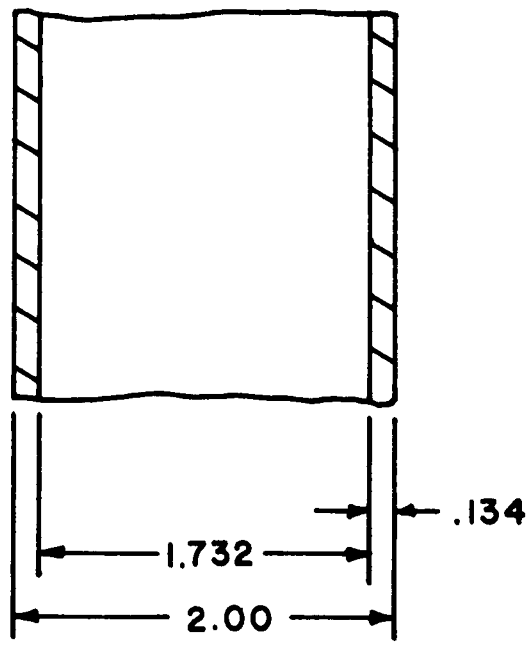
$P_{WORK} = 3500$ PSI ; $P_{TEST} = 5250$ PSI

CYL. WALL STRESS :

$$\sigma = \frac{5250 \times 7.00}{2 \times .80} = \underline{23,000 \text{ PSI}}$$

DOME WALL STRESS, MERIDIAN SECTION :

$$\sigma = \frac{5250 \times 3.5}{(.9 + 1.9)} = \underline{\underline{6,600 \text{ PSI}}}$$

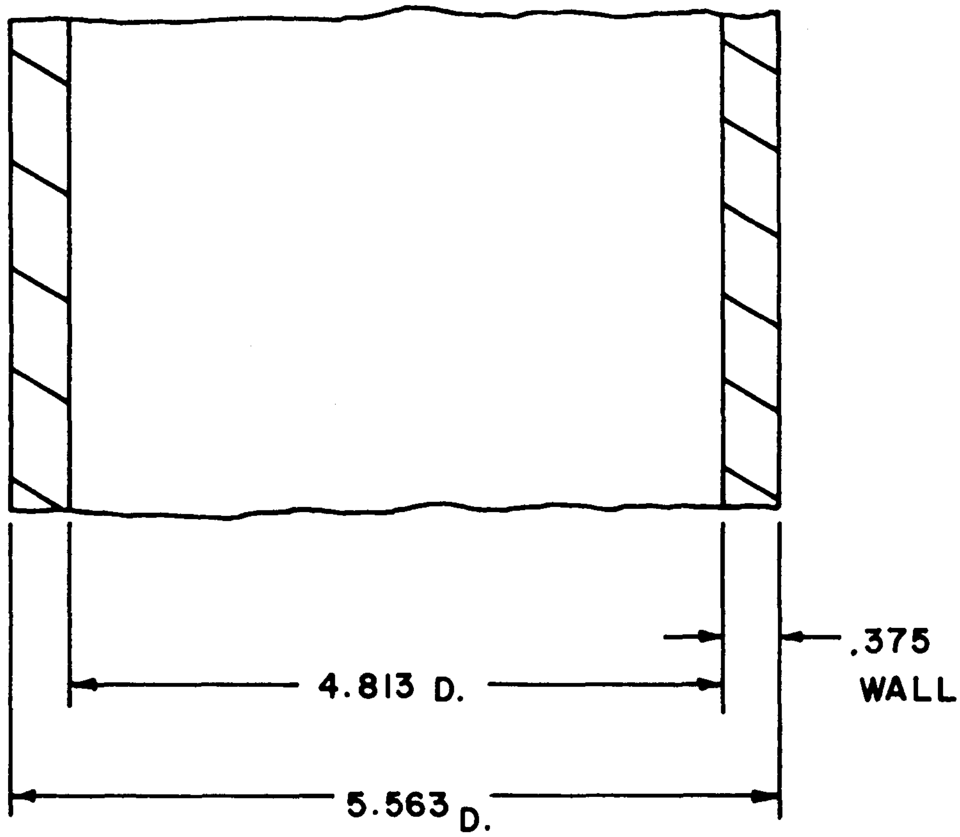


TUBE — 30

P_{WORK} = 3500 PSI ; P_{TEST} = 5250 PSI

WALL STRESS:

$$\sigma = \frac{5250 \times 1.732}{2 \times .134} = \underline{\underline{34{,}000 \text{ PSI}}}$$



5" PIPE, SCHEDULE 80 S, OUTSIDE CONNECTIONS TO THE MANIFOLD ASSEMBLY

$P_{WORK} = 3500$ PSI ; $P_{TEST} = 5250$ PSI

WALL STRESS:

$$\sigma = \frac{5250 \times 4.813}{2 \times .375} = \underline{\underline{33{,}800 \text{ PSI}}}$$

VI.

APPENDICES

1. CALIBRATION & MEASUREMENT OF THE MASS FLOW OF GASES

Pressure and temperature taps are provided at selected stations of the manifold system. These are located around the flanges of the inlet and outlet manifold housings. With these taps, accurate measurements and recordings of the static pressure and total (stagnation) temperature can be made during the calibration process. Temperature probes of high recovery factor should be used in measuring the total temperature which can be reduced to static temperature by several well-known thermodynamic equations. The following equations, which are used in Quantum Dynamics' (on-line) electronic mass flow and density computing system, may be suggested:

$$\text{Static Temperature} = \text{Total Temperature} - \frac{u^2}{2gJCp}$$

where, u is the flow velocity which is given precisely by the output of the flowmeters; g is the gravitational constant ($=$ 32.2 ft/sec^2); J is the mechanical equivalence of heat ($=$ 778 ft. lb./BTU); Cp is the specific heat at constant pressure for the gaseous effluent ($\simeq$ 7 R/2 with R as the Universal Gas Constant R $=$ 0.4894 BTU/lb.^{o}F) in unit of BTU/lb/^{o}R.

With the accurate determination of static pressure and static temperature, the density of the gas can be accurately determined by means of the equation of state. In automatic electronic computing systems supplied by Quantum Dynamics, the density value is directly indicated by a meter.

Knowing the precise value of the gas density and the volumetric flowrate, the mass flowrate can be accurately determined. (See Q.D. Bulletin 5.2 for standard model of computing systems). Standard Q.D./E.L. Model 500-PF/T computer, which is a low cost hybrid electronic computer, can automatically provide such computation with an accuracy of better than 0.1%, yielding a digital reading of the mass flowrate (see Elastronics Bulletin 4.1).

2. CALIBRATION & MEASUREMENT OF MASS FLOW OF CRYOGENIC FLUIDS

Beside the method of relying on pressure and temperature for density determination; the density of cryogenic fluids can also be measured directly by means of Quantum Dynamics/Elastronics - Clausius-Mossotti Type Dielectric-to-Density - Converter. Some description of this device is given in Quantum Dynamics/Elastronics Bulletin 5.2 entitled "Cryogenic Measurement Devices."

3. QL FLOWMETERS

See attached Q.D. Bulletins 5.1 and 5.2.

4. CAPABILITY OF METERING TRANSIENT AND DYNAMIC FLOW

Using QD/EL Model FPAC-100 Transient Flowrate Indicator (See attached EL Bulletin 4.2) and a wide-band electronic summing amplifier, or circuit, the transient flow phenomena can be measured and observed reliably and economically. This can be a powerful method for measuring, e.g., valve dynamic characteristics and the transient flow behavior and instability phenomena of flow and propellant systems.

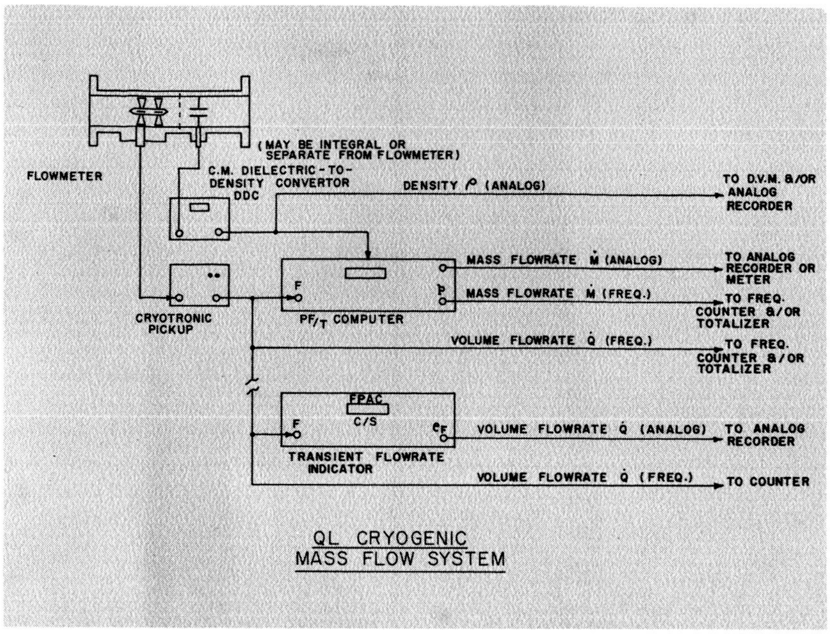


Figure 7. QL Cryogenic Mass Flow System

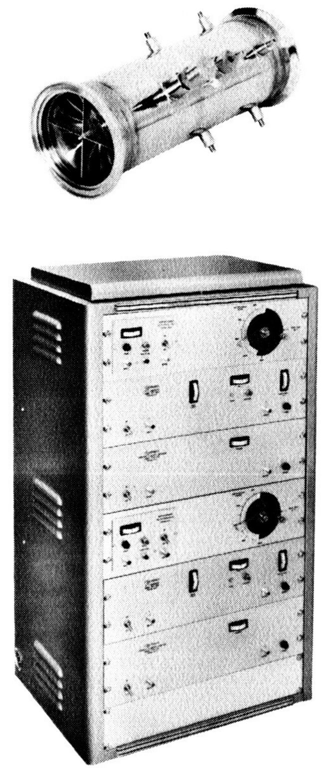


Figure 8. Early Model of Dual-Channel LH_2 Mass/Transient Flow Measurement System

nsfer in aerospace and industrial applications. is system makes possible very high resolution and accurate measurement at exceptionally high flowrates by summing the multichannel frequency outputs; yet the same system also enables the metering of low flowrates with each individual flowmeter. Implementing the smooth-transition manifold design with the use of adjustable Foettinger-Frey vanes, the QL manifold flowmeter system has the following notable features:

- Insures proper distribution of the fluid flow between the individual flow channels under various pressure-head, flowrate, and fluid characteristics.
- Provides means for the precise adjustment of flow distribution with a minimum of detrimental fluid-dynamic phenomena, such as serious cavitation, cross-over transient, vortex, swirling, and other undesirable hydrodynamic and acoustic phenomena.
- Facilitates the use of a number of high-resolution, smaller-sized flowmeters for the precise measurement of large amounts of flow, while at the same time insures that the properties of the effluent (e.g., density) are maintained essentially the same in all flow channels. This can only be done if the distribution of the flow can be adjusted and divided smoothly and evenly.
- Drastically reduces the pressure drop and flow impedance at high flowrates.

With a passive type of manifold, it would be virtually impossible to satisfy the above features while achieving the proper distribution of flow among a multiplicity of channels; as such, the passive manifold is incapable of highly accurate measurement, calibration, and control functions of many channels. Such disadvantages are eliminated in Quantum Dynamics' adjustable-manifold flowmeters.

Existing standard QL adjustable-manifold systems (Fig. 6) are of 3-, 4-, or 5-channel design and of stainless-steel construction. A typical system has flanged inlet and outlet sections of 4.81-in. ID. The individual channels are of 2-inch tubing, designed for operating pressures of up to 3500 psi. As a gaseous-flow calibration system, a 5-channel unit of existing design that uses 2-in. QL flowmeters has a flow range of from 1.5 to 5000 scfm, achieving a count-rate output of 5000 cps at maximum flowrate. For cryogenic flow, the same system has an operating flow range of from 2.5 to 5000 gpm.

SPECIFICATIONS, QUANTOMICS-LIU FLOWMETERS

Effluent: cryogenic hydrogen, helium, nitrogen, oxygen, fluorine, argon, and other gases in liquid and/or vapor-gaseous phases, including mixed-phase fluids and cryogenic fluids in supercritical and superheated states.

Sizes: standard, ½, ⅝, ¾, 1, 1¼, 1½, 2, 3 inches; special, ¼, 4, 5, 8, 16 inches.

Temperature range: 5°K to 370°K.

Flowrate range: consult Quantum Dynamics' engineering and sales staff on size and flow range for your particular application, in view of the consideration that mass-flow range determination involves the state and density of the fluid, pressure drop, measurement resolution, etc.

Accuracy: 0.2% or within.

Linear response range: 50-to-1 or higher; special units have achieved 500-to-1 or higher.

Materials used: special cryogenic-grade stainless steel, alloyed for low-temperature operation.

Coupling effect of sensing element: none.

Associated equipment: vacuum jacket; CM dielectric-to-density converter; PF/T computer; FPAC transient-flowrate indicator. Flowrate (limit-setting) warning devices can be supplied with the basic volumetric flowmeters as additional units for a variety of flow measurement and control functions.

Outputs available: (for general arrangement, see Fig. 7)

Output signal	Basic form	Available form
mass flowrate	frequency	analog
totalized mass flow	totalized pulse number	
volume flowrate	frequency	analog
totalized volume flow	totalized pulse number	
density	analog voltage	frequency
transient (time-varying) flowrate	analog voltage	

MASS FLOW SYSTEMS

Quantum Dynamics' QL flowmeters — when teamed with its CDDC density-measurement unit and compact Model PF/T-500 Mass Flow Computer (Bulletin 4.1) — provide, in one single compact system, accurate readings of mass flowrate, volume flowrate, totalized mass and/or volume flow, and density (Fig. 7). The flowmeter represents an advanced, cryogenic flow-measurement unit that covers flow ranges from very minute to extremely large flowrate (with a QL adjustable-manifold flowmeter system) and provides accurate data from the lowest temperature down through the liquid-solid phase to supercritical temperature regimes.

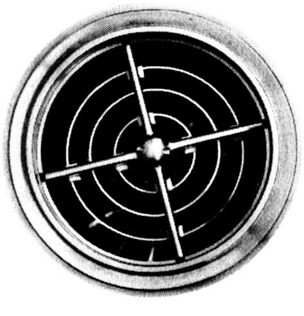


Figure 9. Dielectric Sensing Section

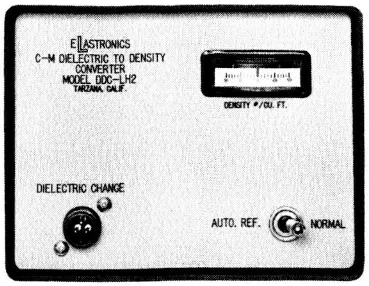


Figure 10. Electronic Section, Dielectric-to-Density Converter

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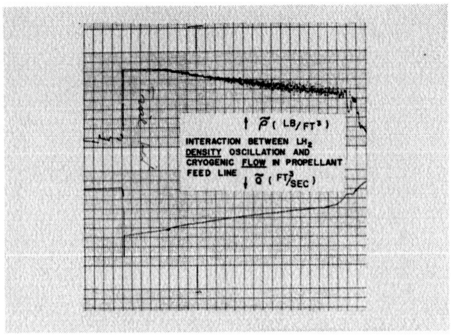

Figure 11. Simultaneous Recording of LH_2 Density and Flowrate

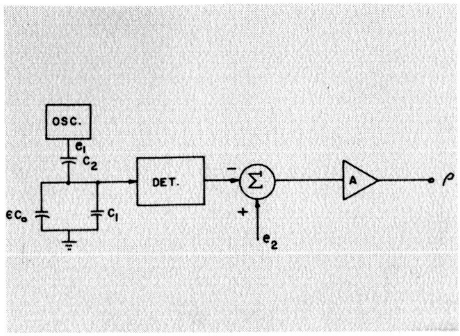

Figure 12. Block Diagram of CDDC Electronic Indicator

CRYOGENIC DENSITY MEASUREMENT DEVICES (Quantum Dynamics/Elastronics CDDC Type Cryogenic Dielectric-to-Density Converter)

From the lowest temperature limit of liquid gases, through the supercritical, to the gaseous regimes, there is encompassed many hundreds of degrees of temperature difference. The equations of the state for each regime differ from one another. Only one density-measurement method is known to be valid throughout the liquid and supercritical regimes;[3] this is the rigorous method used in Quantum Dynamics/Elastronics' Cryogenic Dielectric-to-Density Converter (CDDC): an instrument based on the application of the Lorentz macroscopic dielectric theory. With the CDDC, an accurate reading of density can be obtained directly at high resolution and with large signal levels in volts. The operation and calibration processes are simple; costly cryogenic calibration is not strictly necessary; and the output is an exact linear function of density. In addition, the same instrument provides data on the time-varying density phenomena (Fig. 11) of the fluid, which is often invaluable to the analysis and trouble-shooting of cryogenic flow systems. In fact, the instrument even indicates solid or vapor phase formation in the system. Thus, with a single compact unit, many of the most difficult cryogenic measurement functions (density, phase change, temperature) can be performed with confidence.

THEORY AND OPERATION

The sensor section of the CDDC — which can be a separate or an integral part of the flowmeter (Fig. 9) — is designed to provide stable, sensitive measurement of the dielectric properties of the cryogenic fluid. The electronic section (Fig. 10) then converts the sensed quantity into a direct indication of density by performing a rigorous — not approximate — on-line computation according to the Lorentz-Clausius-Mossotti formula. This formula is well known in macroscopic dielectric theory to be an exact representation of the dielectric-density relationship for cryogenic fluids and all nonpolar liquids and gases:

$$\rho = nM/N = \bar{K}(\varepsilon - 1/\varepsilon + 2)$$

where

n is the number of molecules per unit volume,
N is the Avogadro number,
M is the molecular weight,
ε is the dielectric constant,
$\varepsilon - 1/\varepsilon + 2$ is the Clausius-Mossotti ratio,
$\bar{K} = 3M/4\pi N\alpha$ is a constant with α as the molecular polarizability,
ρ is the density of the cryogenic fluid.

Figure 12 is an illustrative block diagram of a CDDC circuit. It can be shown that when e_1, e_2, C_1, C_2, and A are properly selected, an exact solution of the L-C-M formula can be effected, resulting directly in an accurate and linear indication of the density. It is also obvious from the equation that the present method is essentially one of counting the number of molecules per unit volume, which is valid for space flight as well as ground conditions.

For example, when the density of the fluid is 4.33 lb/ft^3, the output of the CDDC is exactly 4.33 volts. In some models, the cable effect is eliminated by the use of a negative-capacitance compensation; and, an automatic reference check is provided that gives the zero-datum line once every five seconds. The density output can be continuously recorded by means of an oscillograph, showing both the steady and transient pattern of density together with its zero (density) reference line. The CDDC is thus a unique high-resolution and accurate density-measurement device, capable of performing a variety of measurement functions with great simplicity and reliability. For instance, special instruments of this principle have been constructed to provide reading of cryogenic propellent-mass quantities in tank under "zero-g" conditions in substitution of conventional level gauges.

[3]Liu, F. F., "Instrument for the Direct and Continuous Measurement of Liquid Hydrogen Density," **Rev. Sci. Instr.**, to be published in forthcoming issue; Stewart, J. W., **J. Chem. Phys., 40**, 3297 (1964); Froelich, H., **Theory of Dielectrics**, Oxford (1958), pp. 108-111.

SPECIFICATIONS, CDDC TYPE

Applications: a) density measurement of cryogenic fluids in liquid, vapor-gaseous, and solid phases and applicable to mixed-phase fluids; b) as an element of a cryogenic mass flow measurement system; c) as a system's abnormal and subnormal operational warning-monitoring device; d) as an indirect cryogenic temperature-measurement device of high resolution; e) as an indicator for the amount of cryogenic fluid in the tank under "zero-g" space-flight conditions; and others.

Accuracy: within $\pm 1\%$ (high-accuracy model also available).

Input: cryogenic fluids in still or flowing condition, either in single or mixed phase. Fluid may be of any of the following: liquid and/or vapor phase hydrogen, helium, nitrogen, oxygen, fluorine, argon, or any other single component nonpolar fluid.

Output: 0 to 5 volts or emf, which is a direct and linear indication of the cryogenic density. An automatic "zero density reference" signal is provided once every 5 seconds to eliminate effects due to second-order change in the dielectric properties of the cable.

Output impedance: 10 ohms.

Load allowable: 3 ma maximum.

Stability: long-term drift, $\pm 0.2\%$.

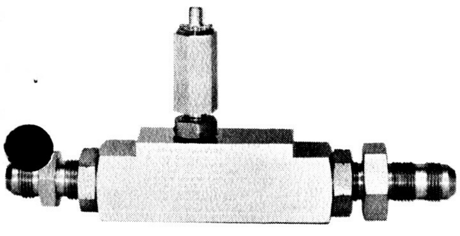

Figure 1. 0.5-In. Liquid Hydrogen Flowmeter

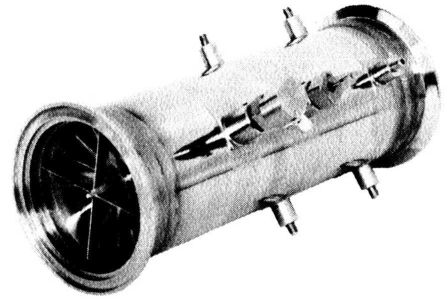

Figure 2. 3 In. Liquid Hydrogen Flowmeter

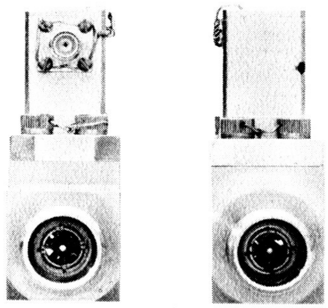

Figure 3. 0.5-In. Liquid Fluorine Flowmeter

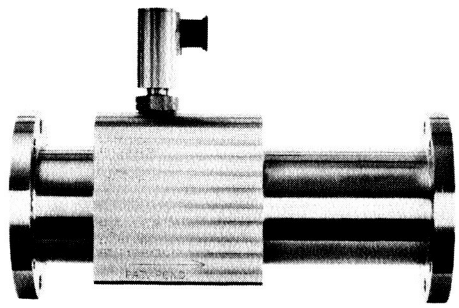

Figure 4. 2 In. Liquid Oxygen Flowmeter

INTRODUCTION

Modern cryogenic technology poses many new problems in measurement techniques. Not only should instruments be usable under a variety of extreme environmental conditions, but also they [illegible]t be designed with a high degree of theoreti[illegible] rigor commensurable with reliability and system engineering considerations. Without these, accuracy and usefulness under extremely low temperatures and cryogenic fluid-dynamic condition become improbable. Moreover, in the face of the high cost and laborious processes involved in cryogenic calibration, many measurement instruments — based on conventional concepts of "brute-force" calibration — are of dubious cost effectiveness.

Cognizant of such considerations, Quantum Dynamics has developed new cryogenic instrumentation for the high-resolution measurement of flow (mass, volumetric, and transient flowrates), density (steady and transient), and temperature (steady and transient) of liquid and super-critical gases at high accuracy and signal levels. Original and theoretically sound approaches are applied to the instrument design. Compared with conventional general-purpose measurement devices, Quantum Dynamics' cryogenic instrumentation represents a line of products that is conceptually rigorous yet meticulously engineered for efficient field applications with liquid and super-critical hydrogen, helium, nitrogen, fluorine, oxygen, and other gases.

VOLUMETRIC FLOWMETERS

(For Measuring Mass Flowrate, Volume Flowrate, Transient Flowrate, and Totalized Flow of Liquid and Super-Critical Gaseous Flows)

DESCRIPTION

THE QUANTOMICS-LIU (QL) series of cryogenic flowmeters is specifically designed for measuring the flow of liquid and super-critical gases. New concepts and rigorous theories are used in these flowmeters, taking into account the characteristics and complex phase (liquid, vapor, and solid not excluded) structure of the cryogenic fluids and including knowledge of both normal and abnormal cryogenic flow phenomena (Fig. 5). Designed with an awareness of the related problems and verified through prolonged experimental testing, the QL cryogenic flowmeters have been confirmed for their conceptual and performance superiorities.

A minimum of constriction is preferred in the QL flowmeters to anticipate and accommodate the often unstable characteristics of cryogenic fluids and to insure a smooth and stable flow-through process. The least amount of perturbation in the fluids' thermodynamic properties is realized through the maintenance of favorable flow impedance,[2] whereupon the pressure drop is also reduced to a minimum. Designed for use with even the most corrosive fluids, such as liquid fluorine, these features are responsible for the durability and accuracy of the QL flowmeters, which have the corrosive-cavitational effects greatly minimized.

These deliberate design efforts, while noteworthy, are of particular importance to modern propulsion and industrial applications where cumulative line-drop and system instabilities are to be minimized. Whereas, in conventional general-purpose flowmeters, it has been the practice to achieve low-range performance through "brute-force" constriction of the entrance or rotor section for favorable Reynolds number effects, such methods can be detrimental to cryogenic applications. In the QL flowmeters, accuracy over a wide flow range is achieved through use of novel design features — features based on knowledge of cryogenic fluid dynamics which, due to the different characteristics of liquid gases, cannot always be dealt with in the same manner as in ordinary liquid flow.

[2]Flow impedance is defined as the ratio of pressure variation to flowrate variation.

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QUANTUM DYNAMICS

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Phone: 213-345-6828
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NEW CONCEPTUAL FEATURES OF QUANTOMICS-LIU SYSTEMS

1. **Highly responsive, near-frictionless, "piggie-back" bearing principle of long operating life.**
2. **Concept of matching flow impedances.**
3. ***Feedback effects due to positive and negative* blade concept.**
4. **Least-constriction configuration with fluid dynamic control device.**
5. **High-resolution, linear density sensing without moving parts or springs.**
6. **Nonretarding and dragless cryotronic pickup.**
7. **Anti-seizure mechanical design.**
8. **Exact electronic computing of density and mass flow.**

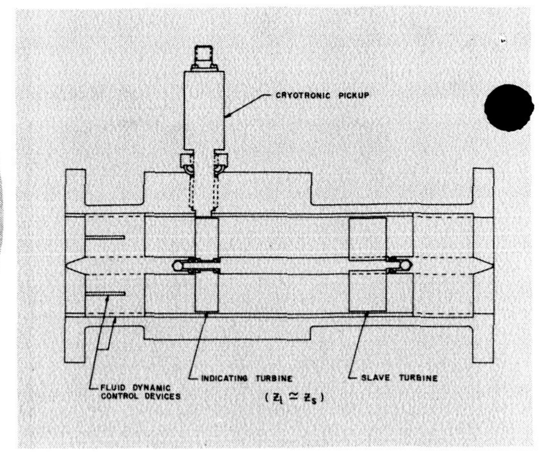

Figure 5.

In terms of general physical features (Fig. 5), the QL flowmeter consists of an "indicating" turbine which rides "piggie-back" on the rotating shaft of a slave turbine. Both turbines respond to the same flow at approximately the same speed, so the relative motion between the indicating turbine and its bearing shaft is maintained at near zero level. In totality, this arrangement then represents a radically new bearing principle which, according to Petroff-Sommerfeld theories, reduces the dynamic friction (or retarding force) to a constant minimum level over an extremely wide range of flowrate. This new concept, in combination with the flowmeter's dragless, cryotronic pickup, accounts for the flowmeter's exceptional response sensitivity. The co-rotational feature also creates two, well matched, impedance zones in the flow field — a feature which is highly beneficial from the fluid-dynamic standpoint. At the same time, an overall feedback effect is also created, which contributes to the enhanced accuracy and stability of metering response. In some larger flowmeters, such as for liquid hydrogen applications, a local feedback effect is also added, utilizing Liu's "negative blade" concept. In terms of fluid-dynamic features, the angle, contour and moment of inertia, etc., of the turbine blades as well as the stream straightening, coupling and profile-control devices are designed to effect the best possible compromise between the theoretical correctness, responsiveness, and adequate strength over a wide range of flow conditions.

To insure reliable and fail-safe operation at low temperature, QL flowmeters use only selected special alloys, metals, and nonmetallic materials. Because the flowmeter does not rely on the magnetic method of sensing, magnetic metal is not permitted in the instrument: the ferritic content of the vital sensing element is kept well below 1 percent. This prevents damage due to "twist" changes or other brittle failures in the crystal structure. The trouble free and long life operation of QL flowmeters is further implemented by an anti-seizure design of the moving element assembly, which automatically adjusts for the thermal contraction and expansion factor, even under the most sudden temperature change.

QL flowmeters use a "cryotronic" sensing method which differs drastically from the conventional magnetic frequency pickups. The greatly increased magnetic coupling of conventional pickups adversely affects the accuracy of cryogenic flow measurement because the field increases by tens or hundreds of times at very low temperatures. Recent literature also indicates that near the critical points, radiating magnetic fields can be generated by the collapse and formation of vapor pockets; such spurious fields are known to have caused erroneous outputs in many conventional magnetic and FM pickups, resulting in signals which are irrelevant to the flow quantities. In contrast, the self-adjusting cryotronic pickups of QL flowmeters are dragless sensors, designed to be completely immune to any such detrimental effects at low temperatures (see Bulletin 5.1). These flowmeters give unhindered freedom of response, high resolution, and high sensitivity of the turbine in metering cryogenic flow, and provide a strong flowrate-proportional signal over a wide range of temperature without the necessity for any manual adjustments.

LARGE FLOWMETERS

Aside from material and other engineering factors, the reliability and fail-safe features of a cryogenic flowmeter are intimately related to the fluid dynamics of the effluent and the dynamic response of the sensing elements. For large-diameter cryogenic flowmeters and/or high flow rates, where the *reliability considerations* are of particular importance, the large sensing element must be made responsive. For, a large mass of "struggling" sensing element is incapable of performing reliable, accurate flow-measurement functions, as is evident by the following simplified differential equation in which the dynamic terms of flowmeter response occupy an important role:

$\tau\dot{\omega} + \omega = K\dot{Q}$*

where

$\tau = C/K\dot{Q}$ is the time constant of the sensing element,

$\dot{Q}$ is the flowrate,

$\omega = K\dot{Q}(1 - e^{-t/\tau})$ is the output frequency of the flowmeter,

K and C are constants.

QL flowmeters of all sizes, in consideration of accuracy and reliability, have always emphasized transient response. Large QL cryogenic flowmeters are often custom designed for specific operations. Such designs are arrived at through methodical analysis and solution of a number of simultaneous equations, so that reliability, measurement accuracy, and resolution are optimized for the particular application. But the basic superiority of these large QL flowmeters is due to the numerous original design features; as a result, these QL flowmeters represent a radical departure from conventional flowmeters, not only with greatly improved reliability and life span but also with considerably higher measurement resolution and accuracy.

ADJUSTABLE-MANIFOLD FLOWMETERS

The QL Adjustable-Manifold Multirange Flowmeter System was developed to fill a need for highly precise and unusually wide-range flow measurement, calibration, control, and automatic fluid

*Liu, F. F., **Archiv. F. Tech. Messen,** 174R, 145 (Nov. 1958); Liu, F. F. and Berwin, T. W., **Rev. Sci. Instr., 29,** 14 (1958); Liu, F. F. et al, **NBS Monograph 67** (1964); Ower, E., **Phil. Mag.,** Ser.7, **23,** 992 (1937).

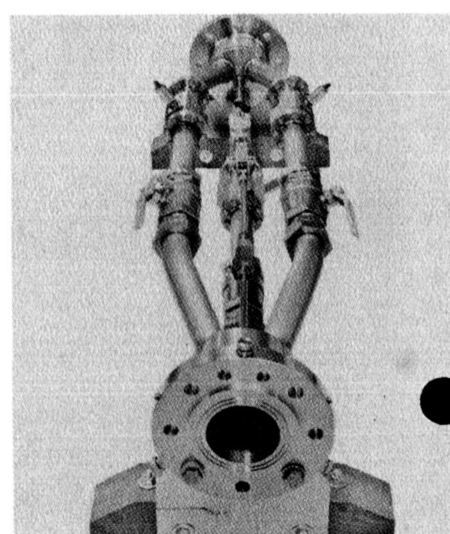

Figure 6. Adjustable-Manifold Flowmeter System

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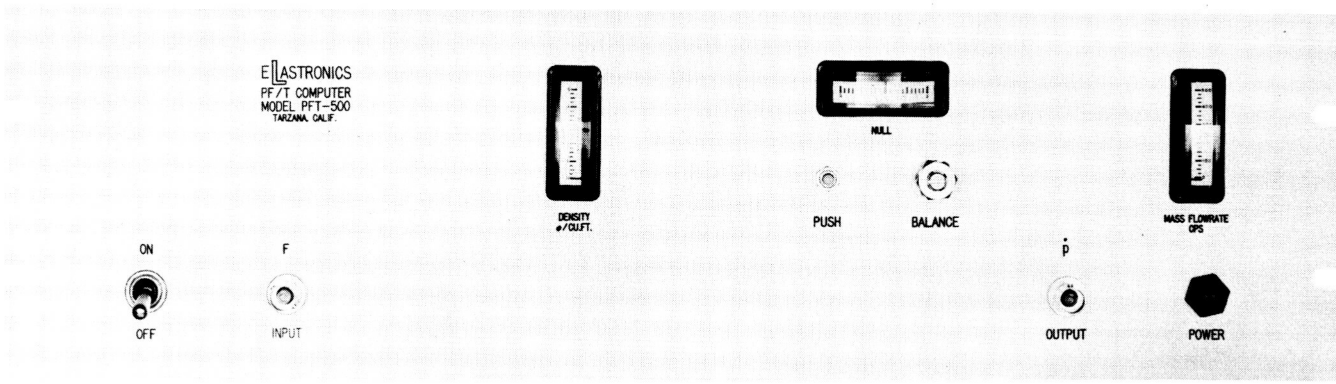
Advanced Electronics and Instrumentation for Scientific Research and Missile Development

Bulletin **4.1**

POWERFUL, VERSATILE MEASUREMENT AND COMPUTING DEVICE FOR PROPULSION AND ELECTRONIC APPLICATIONS

MODEL PF/T-500 MASS-FLOW COMPUTER & ELECTRONIC MULTIPLIER-DIVIDER*



APPLICATIONS

The Quantum Dynamics — Elastronics PF/T Computer is a small, all-solid-state instrumentation computing unit that is designed for a variety of applications, among which are the following:

Accurate computation of the mass flowrate and totalized mass flow of any gas, liquid, or cryogenic fluid, providing output in digital (or analog) form. As a high-accuracy, general-purpose, one-quadrant electronic multiplier-divider for digital and/or analog inputs.

As an on-line computer for the direct determination of the mixture ratio of bipropellant propulsion systems.

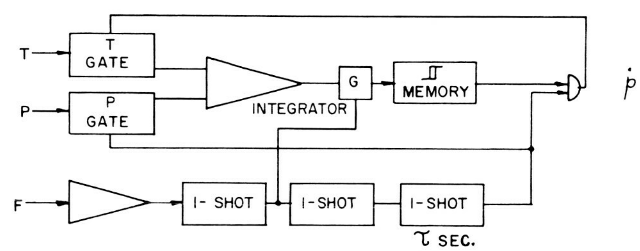
As an on-line computer for the direct determination of total impulse and/or specific impulse.

DESCRIPTION

The PF/T Computer is a small, hybrid computer which accepts an alternating voltage of frequency F and two voltages P and T, and provides output pulses, the average frequency ($\dot{p}$) of which is determined by the equation,

$$\dot{p} = \frac{PF}{T}$$

The actual operation of the system is such that the output pulses occur at the same rate as the input frequency F, except that selected pulses are removed so as to satisfy the above equation. A block diagram of the PF/T Computer is shown below:



The P gate, allowing P to pass, is opened for τ seconds once during each cycle of the F input, thus allowing an average voltage $PF\tau$ to appear after the gate. The T gate, allowing T to pass, opens for τ seconds every time a pulse p occurs; thus, the average voltage appearing after the T gate is $T\dot{p}\tau$. These average potentials are applied to a difference-integrator, which then provides a continuous average of the difference of the two gated outputs. The integrator output is gated once during each cycle of F; this output operates a memory amplifier that detects and memorizes whether the integrator output was greater or less than zero. This memory output controls a coincidence gate, which allows pulses to get through to the T gate and the output. The operation is such that the average integrator input is zero. Therefore,

$$PF\tau = T\dot{p}\tau$$

and

$$\dot{p} = \frac{PF}{T}$$

*Manufactured under license from Quantum Dynamics, Inc.

SPECIFICATIONS, ELASTRONICS MODEL PF/T-500

Inputs

F input	frequency range, 5-500 cps (higher frequency model on request); amplitude required; 1 v rms minimum
P input	$0 \leq P \leq 5$ v; $P \leq T$; in a special model, the P input is applied through Connector J-1 from the C. M. Dielectric-to-Density Converter (for liquid hydrogen and other cryogenic fluid mass-flow measurement)
T input	$0 < T \leq 5$ v; T is adjusted internally at a constant 5.00 volts

Output

$\dot{p}$ output	negative-going pulses from +1 v to −6 v
Accuracy	$\dot{p} = PF/T$ computed to an accuracy of 0.1% of full scale or ±1 count
Power requirement	115 vac

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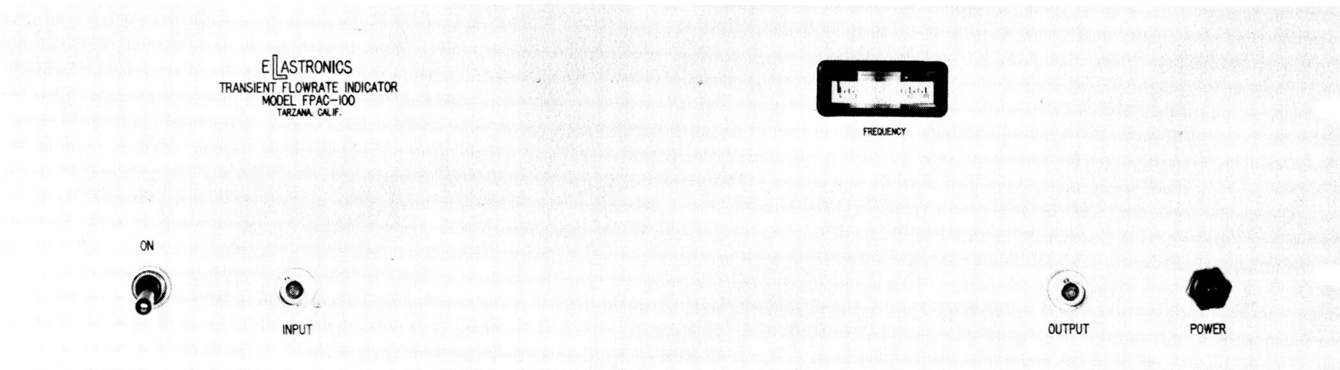
Advanced Electronics and Instrumentation for Scientific Research and Missile Development

Bulletin **4.2**

FOR: DIRECT MEASUREMENT AND RECORDING OF TRANSIENT/DYNAMIC OR STEADY FLOWRATE WITH QUANTUM DYNAMICS Q-L SERIES SPECIAL TURBINE FLOWMETERS.

FOR: GENERAL-PURPOSE ELECTRONIC APPLICATIONS IN CONVERTING DIGITAL DATA INTO CORRESPONDING ANALOG FORM.

MODEL FPAC-100 TRANSIENT FLOWRATE INDICATOR AND ELECTRONIC FREQUENCY-TO-PERIOD-TO-ANALOG COMPUTER*



APPLICATIONS

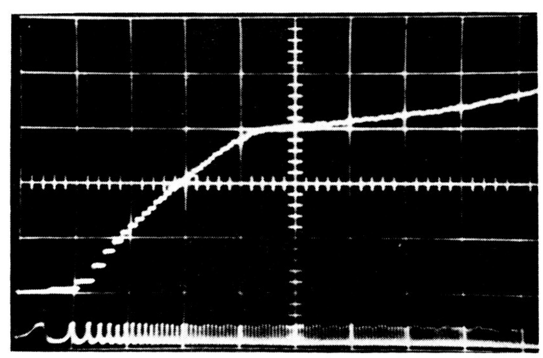
The Quantum Dynamics — Elastronics Model FPAC Transient Flow Indicator and Electronic Frequency-to-Period-to-Analog Computer is an all-solid-state electronic instrument designed for a variety of applications, among which are the following:

The Model FPAC, used with Quantomic Type Special Turbine Flowmeters, makes possible accurate, reliable measurement of high-speed transient/dynamic and steady (liquids, gases, cryogenic fluids) flow phenomena and flow perturbations (e.g., in attitude-control pulse rocket, TVC, combustion instability, etc.). The system provides an output which is linear with flowrate and which has a very fast transient response; the result has been the opening of new avenues in propulsion testing and fluid dynamic investigations.

As an instrument for studying the frequency components of composite wave shapes. As a reliable high-speed digital (pulse-rate, or frequency) to analog data converter for use in various digital and/or hybrid computing facilities.

Special versions of the FPAC can serve as high-speed, nonlinear computing devices; e.g., as a logarithmic time-function generator for functions such as log F(t), or to compute the function $1/t^2$.

For illustrative purposes, the oscillogram below shows "flowrate vs time" of a storable liquid propellant. The recording was made during a sudden, although only moderately fast, opening of a solenoid valve. The system itself, however, has much faster response:



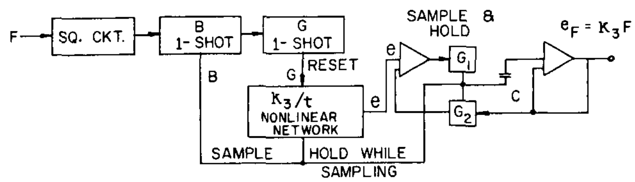
Sweep Rate: 5 milliseconds per division
Vertical: 0.5 volt per division or 0.5 GPM per division

DESCRIPTION

The FPAC Transient Flowrate Indicator is a nonlinear analog computer that accepts a pulse-train signal, or ac voltage of varying frequency, acts on the period T of each cycle, computes the inverse of the time period $e_F = 1/T$, and holds the information for the period of the next cycle. Thus, the output voltage is a level that is linearly proportional to the input frequency $F\ (= 1/T)$, computed once for every cycle. As

*Manufactured under license from Quantum Dynamics, Inc.

such, the unit has a much faster conversion speed in comparison with any conventional frequency-to-dc converter, which relies on the integration of a large number of cycles. A block diagram of the Model FPAC is shown below:



Input F can be a square-wave pulse-train output from any Quantomics flowmeter, or it can be an ac signal shaped into a square-wave by the built-in squaring circuit. The one-shot circuits provide potentials B and G for sampling and resetting. The k_3/t nonlinear network provides a voltage $e = k_3/t$, where t is time and k_3 is a constant, fixed by design at a value of 0.01.

During the sampling period (when the B one-shot is operating), the potential B is present; however, at the beginning of the period $t = T = 1/F$ so that potential $e = k_3/T = k_3F$. This potential is held at $e = k_3F$ for the duration of the sampling period, during which gates G_1 and G_2 are closed and hold capacitor C is charged to the voltage $e = k_3F$. This voltage is held until the next sampling time.

When the sampling is finished, the reset time (when the G one-shot is operating) begins, and voltage e is reset to a fixed level. When the reset time is over, voltage e begins dropping according to the equation $e = k_3t$. At time $t = 1/F$, sampling occurs again, and the sequence of operation is repeated.

SPECIFICATIONS, ELASTRONICS MODEL FPAC-100

Input

Frequency range..... 5-600 cps; higher frequency models on request

Amplitude................ 1.5 v rms, minimum

Impedance............... 20,000 ohms

Output

Voltage..................... $e_F = 0.01$ F, where F = input frequency

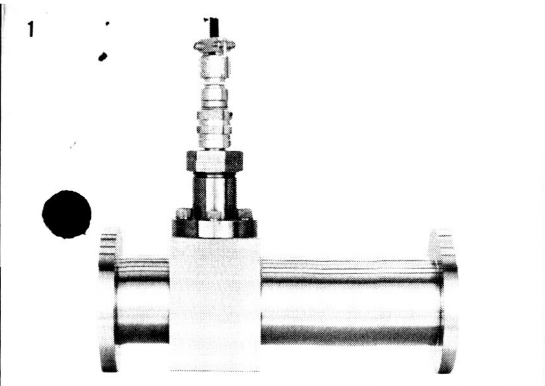
Accuracy.................. ±1% of full scale; high-accuracy model available on request

Impedance............... 10 ohms

Current..................... 6 ma maximum; to drive a 5-ma galvanometer, connect a 1K resistor in series with the output and the galvanometer

Power requirement..... 115 vac

1



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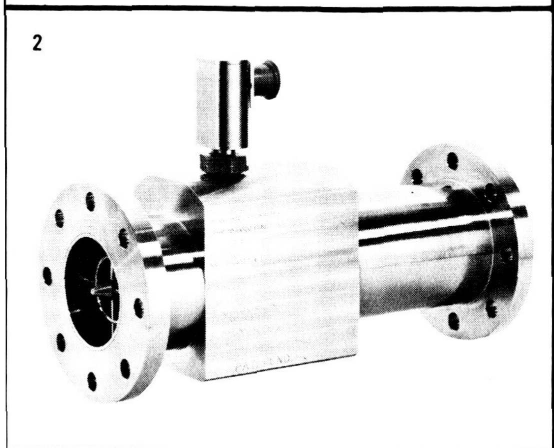

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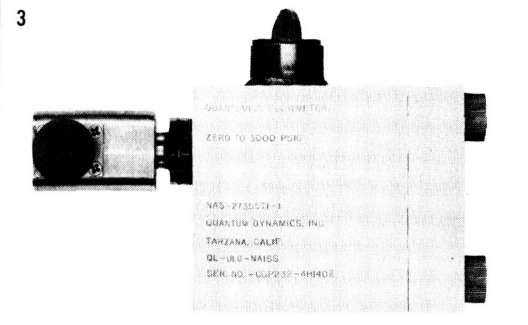

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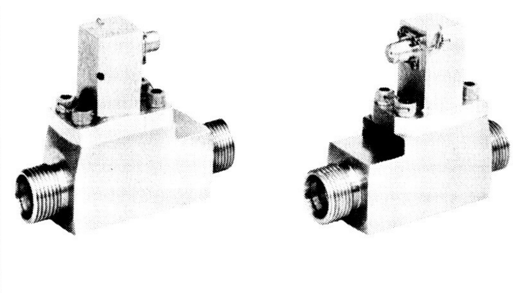

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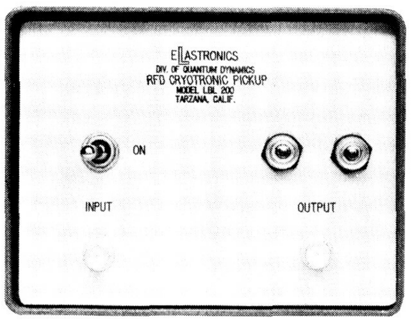

1. High Precision Gaseous, Cryogenic And Supercritical Gaseous Flowmeter With Extremely Low Pressure Drop
2. High-Volume Gaseous Flowmeter
3. Ultra Low Flowrate Gaseous and Supercritical Gaseous Flowmeter
4. Low Flowrate Flowmeters for Gaseous Flow and High Viscosity Fluid Flow Measurement
5. Cryotronic Pickup Electronic Unit and Precision Flow Switch

Bulletin 5.1

HIGH ACCURACY GASEOUS FLOWMETERS FOR VOLUMETRIC AND MASS FLOWRATE MEASUREMENTS*

*U.S. Patent No. [illegible]; foreign patents applied for; conceived and developed by Dr. F. F. Liu

FEATURES

- The only thoroughly proven modern flowmeter for high accuracy, high resolution, and practical measurement of gaseous flow
- Flowrate capability in one package that is equivalent to many units of other makes
- Single calibration and repeatability over a wide range of gas density and compressible flowrates
- High sensitivity at very low flowrate
- Operate over wide range of temperatures from supercritical (cryogenic) gaseous flow to flow at normal temperatures
- Reliable, trouble-free maintenance, long life
- Ability to measure transient flow phenomena, and to serve as accurate digital flow switch
- Make possible high accuracy gaseous mass flow measurement system with digital and totalized outputs

INTRODUCTION

The Quantomics-Liu (QL) series of Gaseous Flowmeters represents an original contribution to the measurement technology of compressible fluid flow.

Rigorously designed on the basis of fluid dynamic and cryogenic theories, engineered and fabricated with precision mechanical and electronic techniques, the new series of high-resolution flowmeters was evolved to meet performance requirements hitherto considered unattainable. The QL flowmeters maintain high accuracy and repeatability over a wide range of fluid density and flowrates, while also achieving sensitivity at extremely low flowrate. They are particularly noted for their ruggedness, trouble-free operation, and long life. Such performance superiority has been thoroughly proven during many years of testing under diverse and extreme conditions.

DESCRIPTION

In terms of general physical features, the QL flowmeter consists of an "indicating" turbine which rides "piggie-back" on the rotating shaft of a slave turbine. Both turbines respond to the same flow at approximately the same speed, so the relative motion between the indicating turbine and its bearing shaft is maintained at near zero level. In totality, this arrangement then represents a radically new bearing principle which, according to Petroff-Sommerfeld theories, reduces the dynamic friction (or retarding force) to a constant minimum level over an extremely wide range of flowrate. This new concept, in combination with the flowmeter's dragless cryotronic pickup, accounts for the flowmeter's exceptional response sensitivity. The co-rotational feature also creates two, well matched, impedance zones in the flow field — a feature which is highly beneficial from

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the fluid-dynamic standpoint. At the same time, an overall feedback effect is also created, which contributes to the enhanced accuracy and stability of metering response. In some larger flowmeters, such as for liquid hydrogen applications, a local feedback effect is also added, utilizing Liu's "negative blade" concept. In terms of fluid dynamical features, the angle, contour and moment of inertia, etc., of the turbine blades as well as the stream straightening, coupling, and profile-control devices are designed to effect the best possible compromise between the theoretical correctness, responsiveness, and adequate strength over a wide range of flow conditions.

To transform turbine response to flowrate into a useful electric signal output completely free from any magnetic coupling and retarding effects, the QL flowmeter's LBL Cryotronic pickup operates in conjunction with its automatic-adjusting electronic unit. A unique, proximity-sensing method based on high-frequency wave absorption phenomena and electronically servoed negative-resistance control technique is used. With this method, no energy is taken away from, or added to, the rotational movement of the turbine — a concept resulting in marked superiority over the magnetic or frequency-modulated pickups, particularly when low gaseous flowrates at low gas densities are measured. Flowrate output is accurately provided by the QL flowmeters in frequency or pulse-rate form; more specifically, the output is in the form of constant amplitude (12 volt peak-to-peak) squarewave pulse train, generated at the LBL electronic unit, and the frequency of the pulse train is linearly proportional to the volumetric flowrate. Very high signal-to-noise ratio is achieved throughout the operating range.

One of the important advantages of the cryotronic pickup is efficiency at cryogenic temperature. Unlike other types of flowmeter pickups, no adjustment or attention is required over a wide range of temperature changes: the pickup is immune to any possible errors induced by spurious magnetic radiation due to the phase changes, cavitation, etc., in cryogenic fluids such as liquid hydrogen.

In terms of accurate performance, a single linear calibration "Frequency Output vs Volumetric Flowrate" prevails over a wide range of density; more specifically, from density as low as 0.065 lb/per cu. ft. to much higher liquid densities. Such a performance advantage makes possible accurate and predictable flow measurement at temperatures ranging from supercritical (cryogenic) hydrogen to sufficiently high ambient temperature, and over a wide range of gas pressure. As long as the gas density is within this wide range, variations of pressure and temperature have virtually no effect on the accuracy of volumetric measurement. Because of these advantages, and when the Quantum Dynamics/Elastronics mass flow electronic computer system is used in conjunction with pressure and temperature measurements, direct indication of the mass flowrate (and totalized mass flow) of gases in digital form can be made at high accuracy. In addition, the high transient response of QL flowmeters also makes possible direct indication of instantaneous dynamic flow quantities when the Elastronics FPAC-100 Transient Flow Indicator is used.

A new flowrate switch for gaseous flowmeters is available from Quantum Dynamics, providing a visible or audible warning or ac or dc control signal as soon as the gaseous flowrate reaches preset limits. These make possible accurate control and automatic monitoring of the flowrate with a single unit for aerospace or industrial applications.

GENERAL SPECIFICATIONS, STANDARD MODELS*

Size (in terms of MS tubing fittings): ultra low gaseous flow (ULG) model, 1/8 in.; flow switch (FS) models, 1/4 in., 1/2 in., 5/8 in., 3/4 in., 1 in., 1 1/4 in., 1 1/2 in.,** 2 in.

Flowrate ranges: ULG meters flowrate down to 0.001 CFM; 2-in gaseous flowmeter measures to 1000 CFM. For flowrates between these limits, a wide choice exists on size of QL flowmeters, depending on user requirements as to line size, pressure drop, and other fluid dynamics considerations. Generally, one QL flowmeter covers a wide range of flowrates, ordinarily equivalent to three flowmeters of other makes; for very high flowrates, use Quantum Dynamics' custom constructed, high precision, adjustable manifolded QL flowmeter system.

Effluent or media: any gas at various pressure and temperature conditions; supercritical hydrogen, oxygen, and other gases at cryogenic temperatures; cryogenic fluids; liquids such as glycol, high-viscosity hydraulic oil, etc.

Output: in frequency or pulse-rate form, suitable for digital indication; high signal-to-noise ratio; output of 12-v peak-to-peak squarewave; amplitude constant from dc to 5000 cps; output frequency at upper limit of flowmeter range generally exceeds 1000 cps

Accuracy: within 0.25 percent for gaseous flow with standard models *

Dynamic range: 50 to 1 or better; special units have achieved 500 to 1 or better

Transient response: can be shorter than 2 msec, depending on density and velocity of media (Elastronics Model FPAC is designed to team with QL flowmeters for transient flow measurements: see Bulletin 4.2)

*Custom models do not fall into this category; performance characteristics are to user specifications.
**1 1/2 inch model has 1.5-inch ID, originally designed for supercritical hydrogen flow.

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